The MACHO project LMC variable star inventory: The discovery of RV Tauri stars and new Type II Cepheids in the LMC

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Received ____________________; accepted ____________________

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ABSTRACT

We report the discovery of RV Tauri stars in the Large Magellanic Cloud. In light and colour curve behaviour, the RV Tauri stars appear to be a direct extension of the Type II Cepheids to longer periods. A single period–luminosity–colour relationship is seen to describe both the Type II Cepheids and the RV Tauri stars in the LMC. We derive the relation: $V_\circ = 17.89(\pm 0.20) - 2.95(\pm 0.12)\log_{10} P + 5.49(\pm 0.35)\overline{(V-R)_\circ}$, valid for Type II Cepheids and RV Tauri stars in the period range $0.9 < \log_{10} P < 1.75$. Assuming a distance modulus to the Large Magellanic Cloud of 18.5, the relation in terms of the absolute luminosities becomes: $M_V = -0.61(\pm 0.20) - 2.95(\pm 0.12)\log_{10} P + 5.49(\pm 0.35)\overline{(V-R)_\circ}$.

1. Introduction

Pulsating variables which occupy the population II instability strip (for example RV Tauri, W Virginis, BL Herculis and RR Lyrae stars) represent an important testing ground for our theories of stellar evolution and pulsation. As low-mass stars of the intermediate disk and halo population they are useful probes of our Galaxy's halo and bulge as well as the outer regions of nearby galaxies.

The period boundaries for Type II Cepheids are determined by the transition from the RR Lyr stars at the short period end to the RV Tauri and long period variables at the long period limit (for a comprehensive review of the population II Cepheids, see Wallerstein & Cox 1984). Those stars with periods between about 1 and 8 days are usually designated BL Her variables while the longer period variables are known as W Vir stars. This nomenclature is useful because the evolutionary state of the two groups is different. The BL Her variables are stars evolving through the instability strip (IS) from the Horizontal Branch towards the asymptotic giant branch (AGB) following the exhaustion of helium in their cores. The W Vir variables are believed to be hydrogen- and helium-shell burning stars which are making blue-loop excursions into the IS from the AGB.

The RV Tauri stars are semiregular pulsating variables which are located in the brightest part of the population II instability strip. As such, there is some overlap in photometric properties with the W Vir Type II Cepheids. A defining characteristic of the RV Tauri variables is a light curve which displays alternating deep and shallow minima. The period between adjacent deep minima is generally in the range 40–150 days and these stars have spectral types F–K with luminosity class Ia–II. Unlike the W Vir stars, most field members of the RV Tauri class exhibit strong infrared excesses indicative of extensive amounts of circumstellar material. From an evolutionary perspective they are thought to be low-mass objects at the termination of their AGB evolution.

Of fundamental importance to our understanding of the RV Tauri variables, and their relationship to the Type II Cepheids, is a knowledge of their physical properties. In particular, our understanding of their mass and evolutionary state depends critically on their luminosities. However, these luminosities are poorly known. There are currently no published identifications of RV Tauri stars in the Magellanic Clouds. Furthermore, there is concern that the handful of stars which are globular cluster members (and for which we have some knowledge of their luminosities) are not of the same spectroscopic type or metallicity as the field RV Tauri stars.

No definitive period–luminosity relation exists. The most commonly used relation (DuPuy 1973) is based on observations of a very small number of low-metallicity globular cluster members and little agreement is seen between this relation and luminosities derived from recent spectroscopic observations of field RV Tauri stars (Wahlgren 1992). Period–luminosity relations exist for the Type II Cepheids (Demers & Harris 1974; Harris 1985; McNamara & Pyne 1994; Nemec, Nemec & Lutz 1994) but in general, these are valid only for shorter periods and the RV Tauri variables are often explicitly excluded from the analyses. Nemec et al. (1994) revived an interesting hypothesis (Arp 1955) that the P-L relation for globular cluster Type II Cepheids (which also included some cluster RV Tauri stars) was actually two parallel relations defined by a harmonic pulsation mode sequence and a first-overtone pulsation mode sequence.

In consequence, the primary goals of this study were as follows:

1. to discover whether variables of the RV Tauri type do exist in the LMC, and
2. to investigate the relationship between the Type II Cepheids and the RV Tauri stars, in particular to determine whether there is a common period–luminosity relationship.

The MACHO project photometry of Large Magellanic Cloud (LMC) variables provides us with an ideal database address the above two issues since we are able to observe both classes of variables in a common environment. The advantages of this are that all stars are at a known common distance, differential reddening is low and large numbers of observations on a common photometric system are available over many cycles. When only smaller or more fragmentary light curve datasets are available, the RV Tauri stars can easily be confused with semi-regular or eclipsing variables.

2. Previous observations of Type II Cepheids in the LMC

The primary sources of optical observations of Type II Cepheids in the LMC are those of Gaposchkin (1970) and Payne-Gaposchkin (1971). These researchers produced photographic light curves, variable type classifications and determined periods for LMC variables from the analysis of Harvard photographic plates. A total of seventeen Type II Cepheids in the LMC were listed in Payne-Gaposchkin (1971). Although some of these Type II Cepheids have periods as long as RV Tauri stars, none were classified as such from their light curves. Harris (1985) states that there are 20 known Type II Cepheids in the LMC, but one (HV13064) has since been shown to be a highly-reddened Type I Cepheid using infrared observations (Laney 1991).

Infrared studies of LMC Type II Cepheids include those by Welch (1987) and Laney (1991). Welch (1987) obtained single-phase JHK observations of nine LMC Type II Cepheids, three of which show infrared excesses at K. Welch suggested that these K-excess stars are simply related to RV Tauri variables. Laney (1991) obtained several JHK observations each of nineteen LMC Type II Cepheid candidates, confirming that four had infrared excesses in the K band.

3. Observations

The MACHO project has been described by Alcock et al. (1992) and Alcock et al. (1995). A dedicated 1.27-m telescope at Mount Stromlo, Australia is used to obtain observations of the LMC year-round (Hart et al. 1996). The camera built specifically for this projects (Stubbs et al. 1993) has a field of view of 0.5 square degrees, which is achieved by imaging at prime focus. Photometric observations of the LMC fields are obtained in two bandpasses simultaneously, using a dichroic beamsplitter to direct the 'blue' (440–590 nm) and 'red' (590–780 nm) light onto 2×2 mosaics of 2048×2048 Loral CCDs. (Hereafter we refer to these bandpasses as $V_{\rm M}$ and $R_{\rm M}$ respectively.) The 15μm pixels map to 0.63 arcsec on the sky. The data were reduced using a profile-fitting photometry routine known as SODOPHOT, derived from DoPHOT (Mateo & Schechter 1989). The output photometry contains flags indicating suspicion of errors due to crowding, poor seeing, array defects and radiation events. For more details of observations and photometric reductions see Alcock et al. 1996a.

For the present study, use was made of the first four years of LMC data, consisting of some 20000 frames distributed over 22 fields concentrated along the bar of the LMC. This sample contains a total of approximately 8 million stars, of which over 40 000 have been found to be variable stars – most newly discovered. Typically, the dataset for a given star covers a timespan of about 1500 days and usually contains 300–1100 good photometric measurements.

4. Analysis

A number of selection criteria were applied to the database of MACHO project variable star photometry in order to produce a list of possible Type II Cepheid and RV Tauri star

candidates. These basic criteria were:

1. 8 d $<$ Period $<$ 100 d

2. $18.5 - 3\log P < R < 18.0$

3. $0.3 < (V - R) < 0.6$.

Although Type II Cepheids with periods shorter than 8 d are present in the MACHO project database, these data were not available for this project. The brighter limit on the R magnitude was chosen so as to exclude the Type I Cepheids. The selection in terms of $(V - R)$ colour is representative of colours of galactic Type II Cepheids and RV Tauri stars. It is quite possible that some relevant variables may have been omitted by the choice of criteria above and it is hoped that this study will be extended in the future by relaxing some of these criteria. In particular it would be useful to extend the long period limit and also to choose a broader range of colour, specifically to include variables with larger values of $(V - R)$.

The $V_{\rm M}$ and $R_{\rm M}$ light curves of the resulting selection of approximately 250 variables were searched for periodicities using a standard fourier-type period-finding code. The phased $V_{\rm M}$ light and $(V - R)_{\rm M}$ colour curves were then visually examined in order to classify the variables. RV Tauri light curves can often be confused with eclipsing binary light variations making the colour information very important in this classification process.

5. Results

5.1. Lightcurves

Thirty-three Type II Cepheid and RV Tauri candidates were discovered. Finder charts for these variables are shown in Figure 1. The internal star identifier, the JD2000.0 coordinates and the fundamental period found from the period analysis are listed in Table 1. A cross check of these variables with the list of seventeen LMC Type II Cepheids given in Payne-Gaposchkin (1971) revealed six stars in common. These designations are included in Table 1. Two stars designated as Type II Cepheids in Payne-Gaposchkin (1971) are also in the MACHO database but we were unable to confirm the Type II Cepheids or RV Tauri star classification due to lack of photometry. These stars (HV 2522 = MACHO*05:26:27.2-66:42:58 and HV 2351 = MACHO*05:16:35.6-68:21:02) were therefore not included in any further analysis but will continue to be observed. The remaining nine HV stars were either not in our MACHO fields, were in a MACHO field without a template or were unlocated due to position errors.

We have identified five of the six Harvard variables listed in Table 1 as RV Tauri candidates rather than Type II Cepheids. Indeed, Gaposchkin (1970) comments on the fact that the majority of the Type II Cepheids discovered in the Harvard survey have long periods:

> "... only four of them have periods that are close to that of the prototype W Virginis. The other 12 are clustered around a period more than twice as large."

Phased $V_{\rm M}$ light and $(V-R)_{\rm M}$ colour curves for all the new Type II Cepheid and RV Tauri variables discovered in the MACHO database to date are shown in Figures 2 and 3. The photometric data have been phased using the fundamental period for the Type II Cepheids and the formal period for stars with periods greater than 20 days. An approximate epoch was chosen such that the 'primary' (or faintest) light minimum of the star occurs

at phase 0.0. Only data free from suspected error are plotted. Typical photometric uncertainties are in the range 1.5–2 per cent. The light curves were qualitatively classified as sinusoidal, crested, flat-topped (following the scheme proposed by Kwee 1967), and RV Tauri-like and these designations are included in Table 1.

5.2. Fourier fits and decomposition parameters

The phased V_{M} light curve of each Type II Cepheid or RV Tauri candidate was fitted with a truncated Fourier series of the fundamental period and up to the 9th order. Typically a fifth order fourier fit was found to be a good representation of the data. Figure 4 shows the 5th order fourier fit to the MACHO photometric data for MACHO*05:37:45.0-69:54:16 which has a double or 'formal' period of 60.816 d. This star displays consistent deep–shallow alternations of its light curve minima and some variability in the depths of the minima is apparent.

The fourier decomposition parameters Φ_{21}, R_{21}, Φ_{31}, and R_{31} are plotted versus $\log P$ in Figure 5. For stars with periods longer than 20 d, the fourier fit using the fundamental period is an increasing poor fit as the light curve becomes more RV Tauri-like. The fourier decomposition parameters become increasingly uncertain as the light curves becomes dominated by the double periodicity. Figure 5 shows there is a progression in Φ_{31} which increases for increasing $\log P$ for all periods.

5.3. Conversion to standard system and absolute luminosities

The V_{M} and R_{M} bandpasses were converted to Kron-Cousins (KC) V and R bandpasses using the latest transformations determined from the ongoing internal calibrations of the MACHO database. Mean V and R magnitudes and mean $(V-R)_{\mathrm{KC}}$ colours were calculated

for each star. To determine the dereddened mean magnitudes we initially adopted an $\overline{E(B-V)}$ to the LMC of 0.074 (Caldwell & Coulson 1985). The standard value of the total to selective extinction, $R_V = A_V/E(B-V) = 3.1$, was used (Cousins 1980). Using the normalised interstellar reddening curve (Whitford 1958) we derive $A_R/A_V = 0.79$ and hence $\overline{E(V-R)} = 0.048$.

Dereddened mean magnitudes were also determined by adopting individual foreground reddenings from the map of galactic foreground colour excess towards the LMC published by Schwering & Israel (1991). These $E(B-V)$ values ranged between 0.07 and 0.15 for the stars in our sample. It was found that adopting these individual foreground reddenings had no significant effect on the derived period–luminosity relationship within the stated uncertainties.

In both the calculations outlined above, no contribution to the reddening from circumstellar material was included. Although it is unlikely that there is much, if any, circumstellar reddening for the Type II Cepheids it it possible that some circumstellar reddening exists for the RV Tauri stars. One star in our sample (MACHO*05:14:18.1-69:12:35) is known to possess an infrared excess at K (Laney 1991). However, as we have no independent means of determining the individual circumstellar reddenings for the other stars in the sample we have ignored this possible contribution.

A distance modulus of 18.5 to the LMC was used to derive the absolute luminosities of the Type II Cepheids and RV Tauri stars. Table 2 presents the mean intrinsic magnitude (V), the adopted $E(B-V)$, the mean dereddened magnitudes ($V_\circ$ and $R_\circ$), the mean intrinsic colour ($(V-R)_\circ$), the quantity W_V ($= V_\circ - 5.49(V-R)_\circ$) and the mean absolute luminosity (M_V). The dereddened HR diagram for the MACHO Type II Cepheids and RV Tauri stars is shown in Figure 6. For the same intrinsic colour the Type II Cepheids have lower luminosities than the RV Tauri stars. This conclusion will only be strengthened

if the RV Tauri stars possess some degree of circumstellar extinction. It is interesting to note that the two Type II Cepheids which fall close to the RV Tauri star 'locus' are stars with periods around 20 d which are beginning to show some RV Tauri characteristics.

6. Discussion

In general it was found that Type II Cepheids with periods greater than ∼20 days display increasing variability in the depth, shape and phasing of their light curve minima. The periodograms of these stars also exhibit increasing strength in the subharmonic frequency (or the double period). When plotted on this double or formal period, as in Figure 2 and 3, the different behaviour of the two minima (and maxima) becomes apparent. Classic RV Tauri behaviour (Pollard et al. 1996) is displayed by many of the stars with 'single' or fundamental periods greater than about 20 days, that is:

- alternating deep ('primary') and shallow ('secondary') minima;
- secondary minima (and maxima) more variable than primary minima (and maxima);
- bluest colours during the rising branch of the light curve, particularly during the rise from the secondary minima.

Figure 7 plots the luminosity, amplitude and colour on the MACHO photometric system versus period. Different symbols are used for the different light curve types in order to reveal any trends. This figure shows a gradual transition in behaviour from the short period Type II Cepheids to the longer period RV Tauri stars. The V_{M} magnitude versus $\log P$ plot (Figure 7(a)) displays a gradually increasing slope for the longer period stars. The amplitude of variation increases (Figure 7 (b)) for increasing period up to a maximum amplitude at around 20 d and then decreases for longer period stars. Results from recent

theoretical studies find increasing complexity and lower amplitudes for the more luminous, low-mass stars of intermediate $T_{\rm eff}$ due to strong non-adiabatic and non-linear effects. The observed preference towards lower amplitudes for higher luminosities noted in Figure 7 is consistent with what is seen for post-AGB transition objects (Sasselov 1992).

As found by previous researchers (Harris 1985, Nemec et al. 1993), the $(V-R)$ colours are seen to get redder for longer period Type II Cepheids. An interesting trend seen in Figure 7 (c) is that the $(V-R)$ colours get bluer again for the RV Tauri stars of longer period. This behaviour has not been noted previously for the galactic RV Tauri stars. However it should be noted that stars with colours redder than $(V-R)=0.6$ were excluded using our selection criteria and it is possible that this may have some effect on this colour trend.

Two stars (MACHO*05:32:54.5-69:35:13 and MACHO*05:40:00.5-69:42:14) are unusual and their classification is tentative. The first star has a very low amplitude light curve with slight variability in the depth of its minima but the period is relatively stable. It appears more like a long-period, low-amplitude W Vir star than an RV Tauri star. The second star displays minima of variable amplitude, but not consistently alternating, which is more reminiscent of some irregular RV Tauri stars or some semiregular variables. As the classification of these two stars is only tentative at this stage, they were not included in the following analysis of the period–luminosity relationship.

6.1. Period–Luminosity relationship

The MACHO database of LMC photometry allows us a direct interpretation of the luminosity and hence the P–L and P–L–C relations for these variables. We have examined the P–L and the P–L–C relations of the Type II Cepheids and RV Tauri stars in the

LMC using both the MACHO light curves and the V and R light curves in the standard (Kron-Cousins) system. Three stars in Table 1 were not included in this analysis. These stars were the two stars of tentative classification described above. The other star excluded from the analysis was HV 5756 (MACHO*05:19:26.9-69:51:52), an eclipsing binary Type II Cepheid (Alcock et al. 1996b) which appears to be brighter and bluer than if it were a single star.

In Figure 8 (a) we plot the galactic P–L relation for Type II Cepheids taken from a number of sources (see also Table 3). The absolute magnitudes of the LMC Type II Cepheids and RV Tauri stars derived in this study are also plotted in this figure. The relations derived from galactic Type II Cepheids appear to be a reasonable representation of the P–L relation for the LMC Type II Cepheids but the extrapolations of these relations to the longer period RV Tauri stars is problematic. The RV Tauri stars appear to be more luminous that the extrapolated P–L relations would suggest. The criteria for classifying the Type II Cepheids as fundamental or harmonic pulsators by Nemec et al. (1994) are unclear and we have been unable to apply these designations to the LMC Type II Cepheids and RV Tauri stars. The relation of DuPuy (1973) is clearly anomalous, but this is probably due to the fact that it based on observations of only three confirmed globular cluster RV Tauri stars.

We have derived a single period–luminosity relationship for the Type II Cepheids and RV Tauri stars in the LMC:

$$\begin{array}{rccc} M_V = & 1.34 & - & 3.07 \log P \\ & \pm 0.45 & & \pm 0.35 \end{array} \qquad \sigma = 0.44 \tag{1}$$

valid for $0.9 < \log P < 1.75$. This P–L relation is displayed in Figure 8 (b). This equation is quite similar to the relation for longer period Type II stars derived by Harris (1985), but there seems to be a alight systematic deviation from the derived relation by the shortest period stars. The possibility that a colour effect is present was investigated by including

a colour term in the multivariate regression analysis. The main contributor to the colour term is the differing effective temperatures of the stars. It also possible that there is some difference in the extinction towards the stars in the sample.

A multivariate linear regression in $\log P$ and $(V-R)_\circ$ with $V_\circ$ as the independent variable allows us to derive a P–L–C relation for the 30 LMC Type II Cepheids and RV Tauri stars:

$$\begin{array}{rcccccc} V_\circ = & 17.89 & - & 2.95\log P & + & 5.49\overline{(V-R)_\circ} & \\ & \pm 0.20 & & \pm 0.12 & & \pm 0.37 & \end{array} \quad \sigma = 0.15 \qquad (2)$$

valid for $0.9 < \log P < 1.75$. If $\log P$ is adopted as the independent variable, then the inverse P–L–C relation becomes:

$$\begin{array}{rcccccc} V_\circ = & 18.06 & - & 3.08\log P & + & 5.47\overline{(V-R)_\circ} & \\ & \pm 0.19 & & \pm 0.13 & & \pm 0.45 & \end{array} \quad \sigma = 0.15 \qquad (3)$$

valid for $0.9 < \log P < 1.75$. In terms of absolute magnitudes, and adopting a distance modulus to the LMC of 18.5, the direct P–L–C relation becomes:

$$\begin{array}{rcccccc} M_V = & -0.61 & - & 2.95\log P & + & 5.49\overline{(V-R)_\circ} \\ & \pm 0.20 & & \pm 0.12 & & \pm 0.37 \end{array} \qquad (4)$$

The quantity W_V $(= V_\circ - \alpha(V-R)_\circ)$ is thus a projection of the P–L–C relation which removes the largest part of the effect of differing effective temperatures and differential absorption (Alcock et al. 1995). The plot of W_V $(= V_\circ - 5.49(V-R)_\circ)$ versus $\log P$ is shown in Figure 9. This figure indicates that the RV Tauri stars are a direct extension of the Type II Cepheids to longer periods and that these population II variables are more accurately represented by a P–L–C relation than a P–L relation (the scatter about the regression line is less than half that shown in Figure 8 where the colour term is omitted).

All the candidate RV Tauri stars that we have identified from the MACHO project LMC variable star database are very luminous variables. This result lends very strong

support to the hypothesis that these stars are in the post-AGB stage of their evolution. The RV Tauri stars therefore appear to represent an important probe of this critical phase of late stellar evolution. The strong link between the behaviour of the Type II Cepheids and the RV Tauri stars is further evidence for a low-mass interpretation for the RV Tauri variables and also may suggest an evolutionary connection between these two classes of variables.

7. Conclusions

A study of the MACHO project LMC variable star database has shown conclusive evidence that variable stars of the RV Tauri class do exist in the LMC. These stars show light and colour curve characteristics that are very similar to their galactic counterparts. A total of thirty three Type II Cepheids and RV Tauri stars candidate were identified in the LMC, although two of these have only tentative classifications. An additional two stars identified as Type II Cepheids in Payne-Gaposchkin (1971) have too little MACHO photometry to confirm their classification.

The discovery of RV Tauri stars in the LMC has enabled us to finally derive accurate absolute luminosities for these objects. The derived absolute magnitudes of the new LMC RV Tauri variables of about –4.5 for variables with fundamental periods of about 50 d ($\log P = 1.7$) lends strong support to the proposal that these objects are luminous, post-AGB stars evolving to the left in the HR diagram.

A progression in behaviour from the short period Type II Cepheids through to the longer period RV Tauri stars in terms of their light and colour curve properties was noted. The variables with periods greater than about 20 d show increasingly strong RV Tauri characteristics.

A single period–luminosity–colour relation is seen to describe both the Type II Cepheids and the RV Tauri stars in the LMC. The continuity in behaviour and properties is strong evidence for an evolutionary connection between these two classes of variables.

8. Future Work

There are a a number of refinements and extensions to the above study that can be made. To discover additional RV Tauri stars in the LMC we need to relax our selection criteria on the MACHO variable star database in order to include variables with longer periods and redder colours. This relaxation of the selection criteria should also allow us to investigate whether any bias was introduced in our derived P–L–C relation. The P–L relation for Type I Cepheids breaks down for the longer period ($> 100\,\mathrm{d}$) Cepheids – it is not known whether the RV Tauri stars also show this behaviour. Complications in this investigation will be the increasing complexity of the light curve behaviour of these longer period stars and the possibility that larger amounts of circumstellar reddening may be present, affecting our results in the visual bandpasses. There are indications that some of the longer period RV Tauri stars do show near-infrared excesses (Welch 1987, Laney 1991).

The post-AGB phase of evolution is believed to be extremely fast and long-term two-colour photometry on a common photometric system, such as what has been obtained to date in the MACHO project, will be invaluable in looking for period and colour changes due to evolutionary effects. In addition, this database will allow us to investigate the relatively recent suggestion that the RV Tauri stars show evidence of chaotic behaviour (Buchler & Kovacs 1987, Kovacs & Buchler 1988, Buchler et al. 1995) and the Type II RV Tauri sequence in the LMC will be an extremely useful tool in exploring the predicted trend in chaotic behaviour with $T_{\rm eff}$ (or luminosity).

More fields from the MACHO project microlensing survey should be examined to increase the current sample of Type II Cepheids and RV Tauri stars in the LMC. In addition a search for Type II Cepheids and RV Tauri star candidates in the SMC would be useful in investigating the effects of the lower metallicity on the group characteristics and properties.

We would like to thank Drs Michael Albrow and Luis Balona for computer assistance in the data analysis. KRP was a Postdoctoral Research Fellow at the South African Astronomical Observatory (SAAO) during this work. The SAAO is a National Research Facility operated by the Foundation for Research Development. We are very grateful for the skilled support given our project by the technical staff at the Mt. Stromlo Observatory. Work performed at LLNL is supported by the DOE under contract W7405-ENG-48. Work performed by the Center for Particle Astrophysics on the UC campuses is supported in part by the Office of Science and Technology Centers of NSF under cooperative agreement AST-8809616. Work performed at MSSSO is supported by the Bilateral Science and Technology Program of the Australian Department of Industry, Technology and Regional Development. KG acknowledges a DOE OJI grant, and CWS and KG thank the Sloan Foundation for their support.

Table 1. Period and light curve analysis of the LMC Type II Cepheid and RV Tauri stars.

star id	α (2000.0)	δ	Period (days)	$\log P$	$V_{\rm M}$ (mag)	$\Delta V_{\rm M}$ (mag)	$R_{\rm M}$ (mag)	$\Delta R_{\rm M}$ (mag)	type[a]	comments
12.10318.52	05 43 47.2	-70 42 39	8.240	0.916	-7.13	0.59	-7.42	0.46	s	
81.8756.207	05 34 37.8	-70 01 07	9.309	0.969	-6.94	0.54	-7.28	0.45	s	
1.3812.61	05 03 59.3	-68 53 24	9.387	0.973	-7.64	0.27	-7.80	0.22	s	
10.4040.38	05 05 11.8	-69 45 55	9.622	0.983	-7.65	0.43	-7.79	0.32	s	
80.6469.135	05 20 20.7	-69 12 21	10.509	1.022	-7.16	0.36	-7.51	0.27	s	
80.6590.137	05 21 18.8	-69 11 47	11.442	1.058	-7.49	0.92	-7.68	0.68	c	
3.7332.39	05 25 14.9	-68 09 12	12.704	1.104	-7.17	1.02	-7.52	0.80	f	
6.6696.72	05 21 35.2	-70 13 26	12.902	1.111	-7.16	0.63	-7.55	0.51	s	
10.4162.33	05 06 28.7	-69 43 58	13.246	1.122	-7.19	0.42	-7.53	0.37	s	
80.6475.2289	05 20 10.4	-68 48 40	13.925	1.144	-7.26	1.30	-7.62	0.95	f	
81.9006.64	05 36 02.8	-69 27 16	14.337	1.156	-7.02	0.95	-7.48	0.77	f	
47.2611.589	04 56 15.9	-68 16 16	14.469	1.160	-7.10	1.14	-7.50	0.92	f	
19.4425.231	05 07 38.9	-68 20 06	14.752	1.169	-7.63	0.87	-7.90	0.61	c	
2.5877.58	05 16 35.6	-68 21 02	14.855	1.172	-6.55	1.03	-7.15	0.83	f	
1.3808.112	05 04 07.8	-69 07 31	14.906	1.173	-6.81	1.04	-7.30	0.84	f	
14.8983.1894	05 36 01.7	-71 00 12	15.391	1.187	-7.25	1.08	-7.63	0.91	f	
2.5025.39	05 11 21.5	-68 40 12	16.602	1.220	-7.33	1.10	-7.66	0.90	f	
9.5117.58	05 11 49.3	-70 34 11	16.747	1.224	-7.57	1.12	-7.93	0.92	f	
10.3680.18	05 02 53.3	-69 36 58	17.127	1.234	-7.54	1.04	-7.92	0.88	f	
78.6338.24	05 19 26.9	-69 51 52	17.560	1.245	-8.32	0.57	-8.48	0.52	c	HV 5756
2.5026.30	05 11 33.5	-68 35 54	21.486	1.332	-7.46	1.25	-7.88	0.97	f/r	HV 13025
78.6698.38	05 21 49.3	-70 04 35	24.848	1.395	-8.28	0.95	-8.64	0.71	c/r	
77.7069.213	05 23 43.5	-69 32 07	24.935	1.397	-7.24	1.27	-7.67	1.05	r	
82.8041.17	05 29 38.8	-69 15 12	26.594	1.425	-8.01	1.01	-8.38	0.86	f/r	
81.9362.25	05 37 45.0	-69 54 16	30.408	1.483	-7.77	1.22	-8.26	1.04	r	
14.9582.9	05 39 33.1	-71 21 55	31.127	1.493	-8.64	0.94	-8.91	0.75	r	HV 12631
19.3694.19	05 03 05.0	-68 40 25	31.716	1.501	-8.88	0.93	-9.10	0.72	r	HV 2281
78.5856.2363	05 16 47.5	-69 44 15	41.118	1.614	-8.94	1.00	-9.19	0.76	r	HV 2423
81.8520.15	05 32 54.5	-69 35 13	42.079	1.624	-9.29	0.39	-9.42	0.29	s?	
82.8405.15	05 31 50.9	-69 11 46	46.542	1.668	-9.78	0.70	-9.86	0.54	r	
81.9728.14	05 40 00.5	-69 42 14	47.019	1.672	-9.63	0.40	-9.95	0.26	r?	
79.5501.13	05 14 18.1	-69 12 35	48.539	1.686	-9.52	0.79	-9.71	0.65	r	HV 915
47.2496.8	04 55 43.2	-67 51 10	56.224	1.750	-9.03	0.90	-9.48	0.68	r	

[a] s=sinusoidal, c=crested, f=flat-topped, r=RV Tauri like, ?=uncertain classification

Table 2. Period and luminosity data for the LMC Type II Cepheid and RV Tauri stars.

star id	Period days	$\log P$	V (mag)	$E(B-V)$ (mag)	$V_\circ$ (mag)	$R_\circ$ (mag)	$(V-R)_\circ$ (mag)	W_V	M_V
12.10318.52	8.240	0.916	17.07	0.15	16.61	16.32	0.291	15.01	-1.89
81.8756.207	9.309	0.969	17.17	0.12	16.80	16.45	0.348	14.89	-1.70
1.3812.61	9.387	0.973	16.31	0.13	15.90	15.72	0.182	14.90	-2.60
10.4040.38	9.622	0.983	16.51	0.14	16.08	15.88	0.198	14.99	-2.42
80.6469.135	10.509	1.022	17.05	0.09	16.77	16.37	0.394	14.60	-1.73
80.6590.137	11.442	1.058	16.72	0.08	16.47	16.18	0.297	14.84	-2.03
3.7332.39	12.704	1.104	17.00	0.07	16.79	16.40	0.387	14.66	-1.71
6.6696.72	12.902	1.111	16.86	0.12	16.49	16.15	0.341	14.62	-2.01
10.4162.33	13.246	1.122	16.95	0.14	16.52	16.19	0.329	14.71	-1.98
80.6475.2289	13.925	1.144	16.75	0.08	16.50	16.13	0.370	14.47	-2.00
81.9006.64	14.337	1.156	16.88	0.09	16.61	16.25	0.358	14.64	-1.89
47.2611.589	14.469	1.160	16.89	0.13	16.49	16.13	0.355	14.54	-2.01
19.4425.231	14.752	1.169	16.16	0.13	15.75	15.53	0.222	14.54	-2.75
2.5877.58	14.855	1.172	17.31	0.11	16.97	16.50	0.464	14.42	-1.53
1.3808.112	14.906	1.173	17.26	0.14	16.82	16.40	0.423	14.50	-1.68
14.8983.1894	15.391	1.187	16.90	0.14	16.46	16.10	0.364	14.46	-2.04
2.5025.39	16.602	1.220	16.58	0.13	16.18	15.87	0.308	14.49	-2.32
9.5117.58	16.747	1.224	16.49	0.14	16.05	15.73	0.318	14.30	-2.45
10.3680.18	17.127	1.234	16.58	0.14	16.15	15.82	0.329	14.34	-2.35
78.6338.24	17.560	1.245	15.68	0.08	15.43	15.19	0.239	14.12	-3.07
2.5026.30	21.486	1.332	16.44	0.13	16.03	15.67	0.361	14.05	-2.47
78.6698.38	24.848	1.395	15.69	0.12	15.25	14.93	0.323	13.48	-3.25
77.7069.213	24.935	1.397	16.57	0.08	16.32	15.90	0.427	13.98	-2.18
82.8041.17	26.594	1.425	15.99	0.08	15.74	15.34	0.399	13.55	-2.76
81.9362.25	30.408	1.483	16.09	0.12	15.72	15.34	0.377	13.65	-2.78
14.9582.9	31.127	1.493	15.48	0.12	15.10	14.84	0.259	13.68	-3.40
19.3694.19	31.716	1.501	15.29	0.13	14.89	14.64	0.248	13.53	-3.61
78.5856.2363	41.118	1.614	15.10	0.12	14.72	14.44	0.288	13.14	-3.78
81.8520.15	42.079	1.624	14.64	0.10	14.33	14.20	0.124	13.65	-4.17
82.8405.15	46.542	1.668	14.26	0.09	13.98	13.77	0.208	12.83	-4.52
81.9728.14	47.019	1.672	14.31	0.10	14.00	13.74	0.267	12.54	-4.50
79.5501.13	48.539	1.686	14.48	0.12	14.11	13.89	0.215	12.93	-4.39
47.2496.8	56.224	1.750	14.97	0.11	14.63	14.23	0.394	12.46	-3.87

Table 3. Period–luminosity relationships for Type II Cepheids.

relation $M_V =$	validity	note	reference
$-0.13 - 1.90\log P$	$0.0 < \log P < 1.3$		Dickens & Carey (1967)
$-5.3\ + 0.042P$	$1.47 < \log P < 1.72$		DuPuy (1973)
$-0.08 - 1.59\log P$	$0.0 < \log P < 1.3$		Demers & Harris (1974)
$-0.08 - 1.59\log P$	$0.0 < \log P < 1.1$		Harris (1981)
$+2.13 - 3.60\log P$	$1.1 < \log P < 1.6$		Harris (1981)
$+0.20 - 1.93\log P$	$-0.2 < \log P < 1.53$	b	Nemec et al. (1994)
$-0.25 - 1.93\log P$	$-0.2 < \log P < 1.53$	c	Nemec et al. (1994)
$+1.34 - 3.07\log P$	$0.9 < \log P < 1.75$		this study
$-0.61 - 2.95\log P + 5.49(V-R)_{\circ}$	$0.9 < \log P < 1.75$		this study

[b]assuming [Fe/H] = –2 and fundamental mode of pulsation

[c]assuming [Fe/H] = –2 and first-harmonic mode of pulsation

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FIGURE CAPTIONS

Fig. 1.— The finding charts for the thirty three MACHO Type II Cepheids and RV Tauri stars in the LMC. The target stars are indicated with crosshairs. North is to the top and east is to the left. The maximum size of the charts is 3 arcmin × 3 arcmin.

Fig. 2.— The $V_{\rm M}$ light curves for the LMC Type II Cepheids and RV Tauri stars described in this paper. The stars with periods less then 20 d (the Type II Cepheids) are plotted on the 'single' or fundamental period, while the stars with periods greater than 20 d (generally RV Tauri stars) are plotted on the 'double' or formal period. These periods are indicated at the bottom of each panel. The variables are plotted between phases 0.0 and 1.5 in order to reveal continuity. The large ticks on the vertical axis correspond to 0.5 magnitudes.

Fig. 3.— The $(V-R)_{\rm M}$ colour curves for the Type II Cepheids and RV Tauri stars in the LMC. Periods and epochs are as for Figure 2. The large ticks on the vertical axis correspond to 0.2 magnitudes.

Fig. 4.— The $V_{\rm M}$ light curve for MACHO*05:37:45.0-69:54:16 plotted together with the 5th order fourier fit to the photometric data. This star has a 'formal' period of 60.816 d.

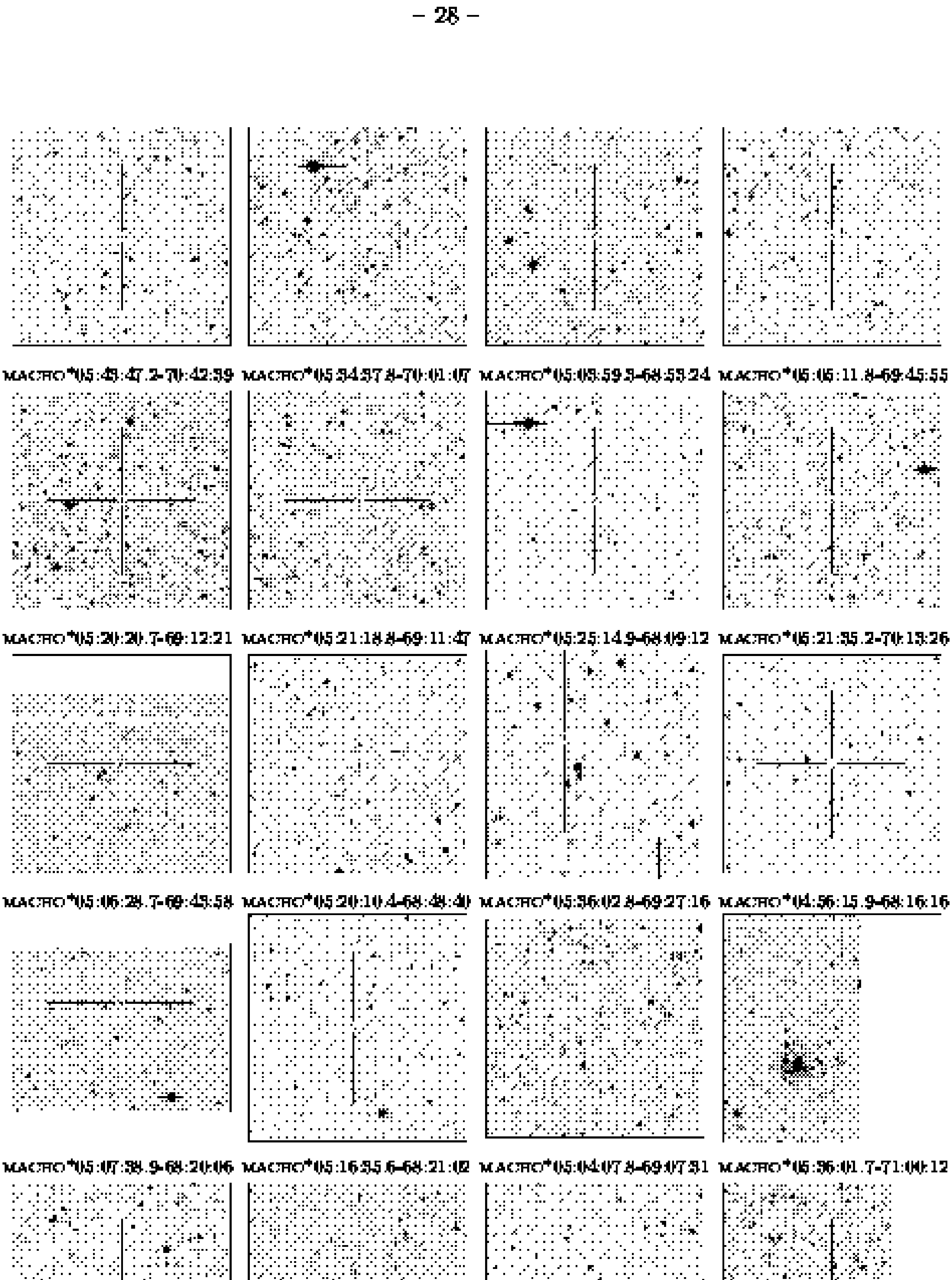
Fig. 5.— The fourier parameters Φ_{21}, R_{21}, Φ_{31} and R_{31} are plotted *vs* $\log P$. Type II Cepheids are plotted using symbols corresponding to their light curve appearance: sinusoidal (crosses), crested (open triangles) and flat-topped (open squares). RV Tauri stars are plotted using open circles and stars of uncertain classification (see text) are plotted using asterisks.

Fig. 6.— The HR diagram for the Type II Cepheids and RV Tauri stars in the LMC. Symbols are as for Fig. 7. The RV Tauri stars are brighter than the Type II Cepheids for a particular intrinsic colour. The bluest stars tend to be the short period Type II Cepheids and the longest period RV Tauri stars.

Fig. 7.— The a) period–luminosity, b) period–amplitude and c) period–colour diagrams for the Type II Cepheids and RV Tauri stars in the LMC. The luminosity is the mean $V_{\rm M}$ magnitude, the amplitude is the peak-to-peak amplitude determined from the fourier fit to the $V_{\rm M}$ light curve and the colour is the mean $(V-R)_{\rm M}$ colour. Symbols are as for Fig. 5.

Fig. 8.— Absolute luminosities of the LMC Type II Cepheids and RV Tauri stars (circles) from the MACHO photometric database are plotted *vs* $\log P$. (a) Period–luminosity relations for galactic Type II Cepheids are displayed. Solid lines: Nemec et al. (1994) fundamental (lower line) and harmonic (upper line) sequences assuming [Fe/H] = –2; dotted line: Harris (1985); dashed line: DuPuy (1973). (b) Period–luminosity relation for the LMC Type II Cepheids and RV Tauri stars from MACHO observations. Stars that were omitted from the analysis (see text) are indicated by triangles.

Fig. 9.— Period–luminosity–colour relation for the Type II Cepheids and RV Tauri stars in the LMC. The quantity $(V_\circ - 5.49\overline{(V-R)_\circ})$ is plotted *vs* $\log P$. Type II Cepheids and RV Tauri stars (circles) are plotted using the 'single' or fundamental period. The solid line is the direct regression relation while the dotted line is the inverse regression relation. Stars that were omitted in deriving the P–L–C relation (see text) are indicated by triangles.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MACHO*05:06:28.7-69:45:58
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MACHO*04:56:15.9-68:16:16
MACHO*05:07:58.9-68:20:06
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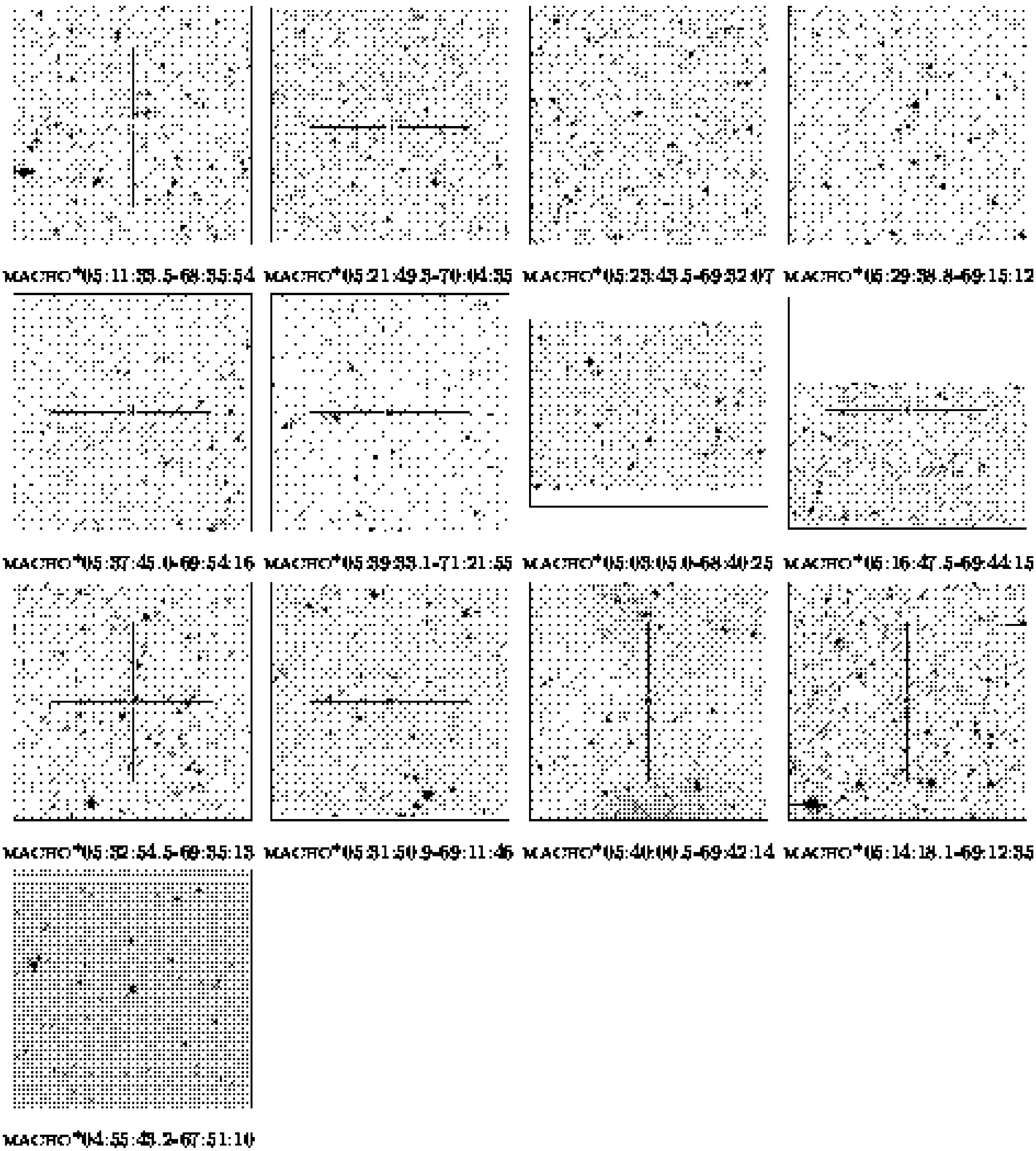
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MACHO*05:37:45.0-69:54:16
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MACHO*05:08:05.0-68:40:25
MACHO*05:16:47.5-69:44:15
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MACHO*05:31:50.9-69:11:46
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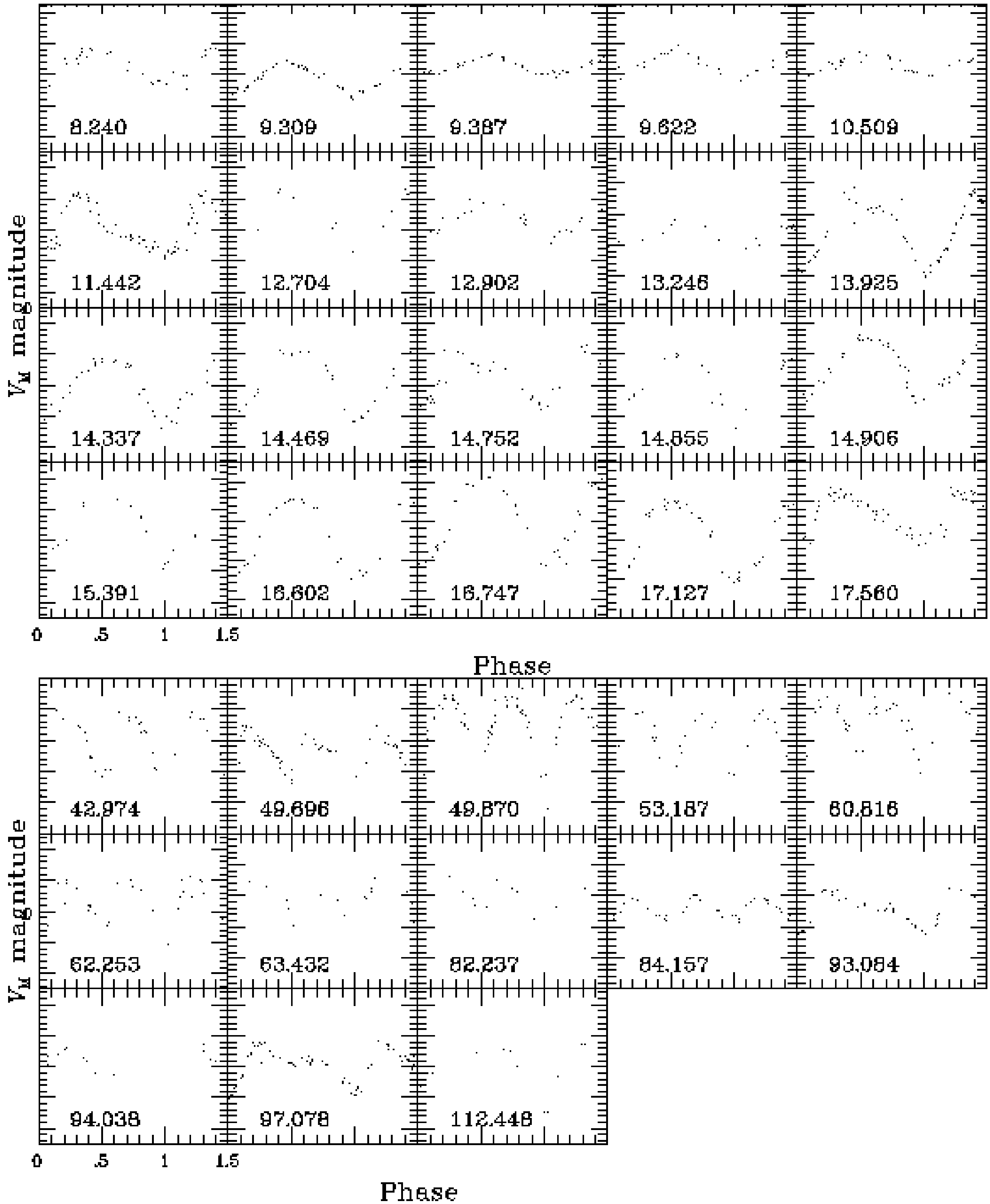
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14.906
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16.602
16.747
17.127
17.560
V_M magnitude
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.5
1
1.5
Phase
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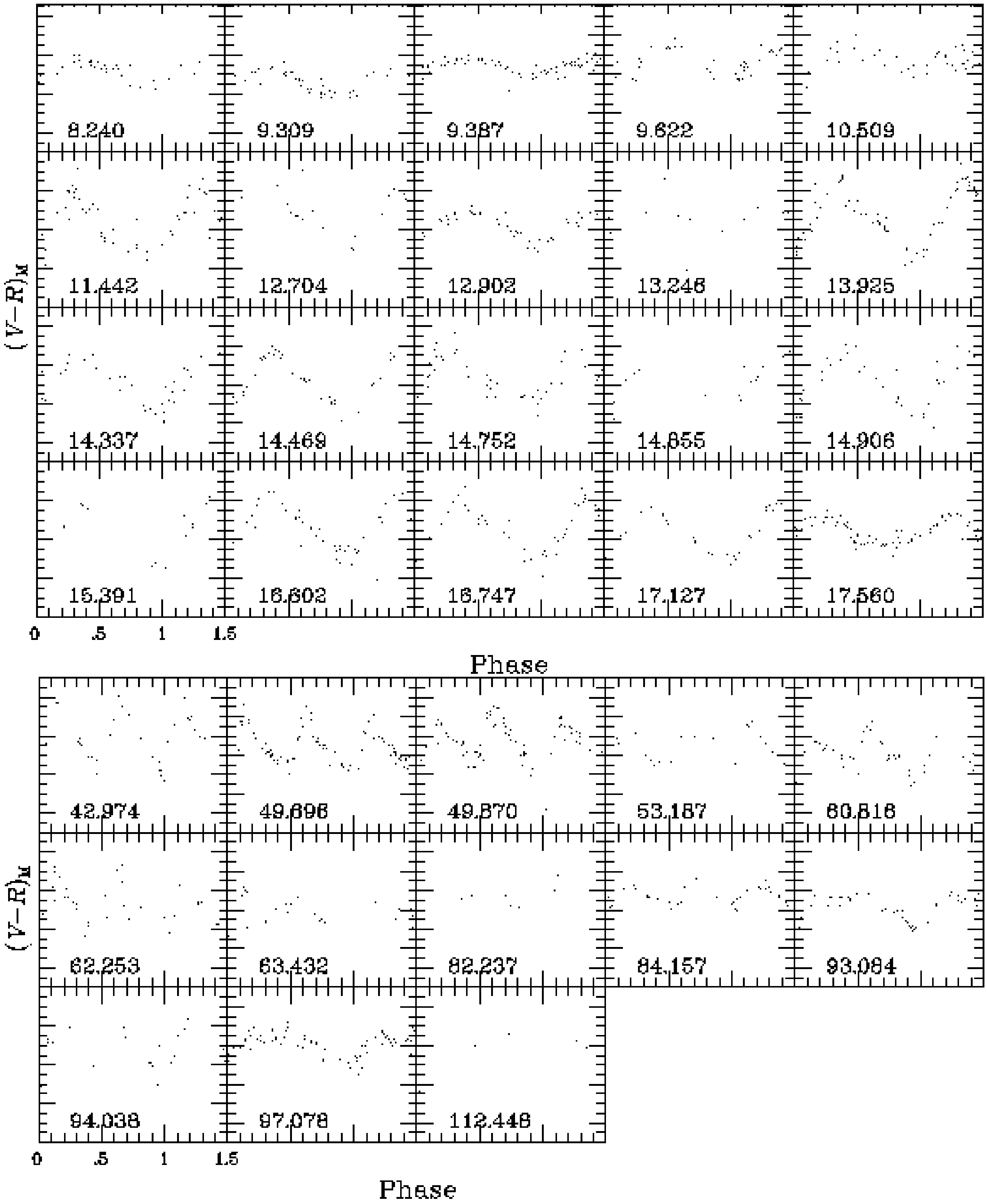

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17.560
$(V-R)_M$
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Phase
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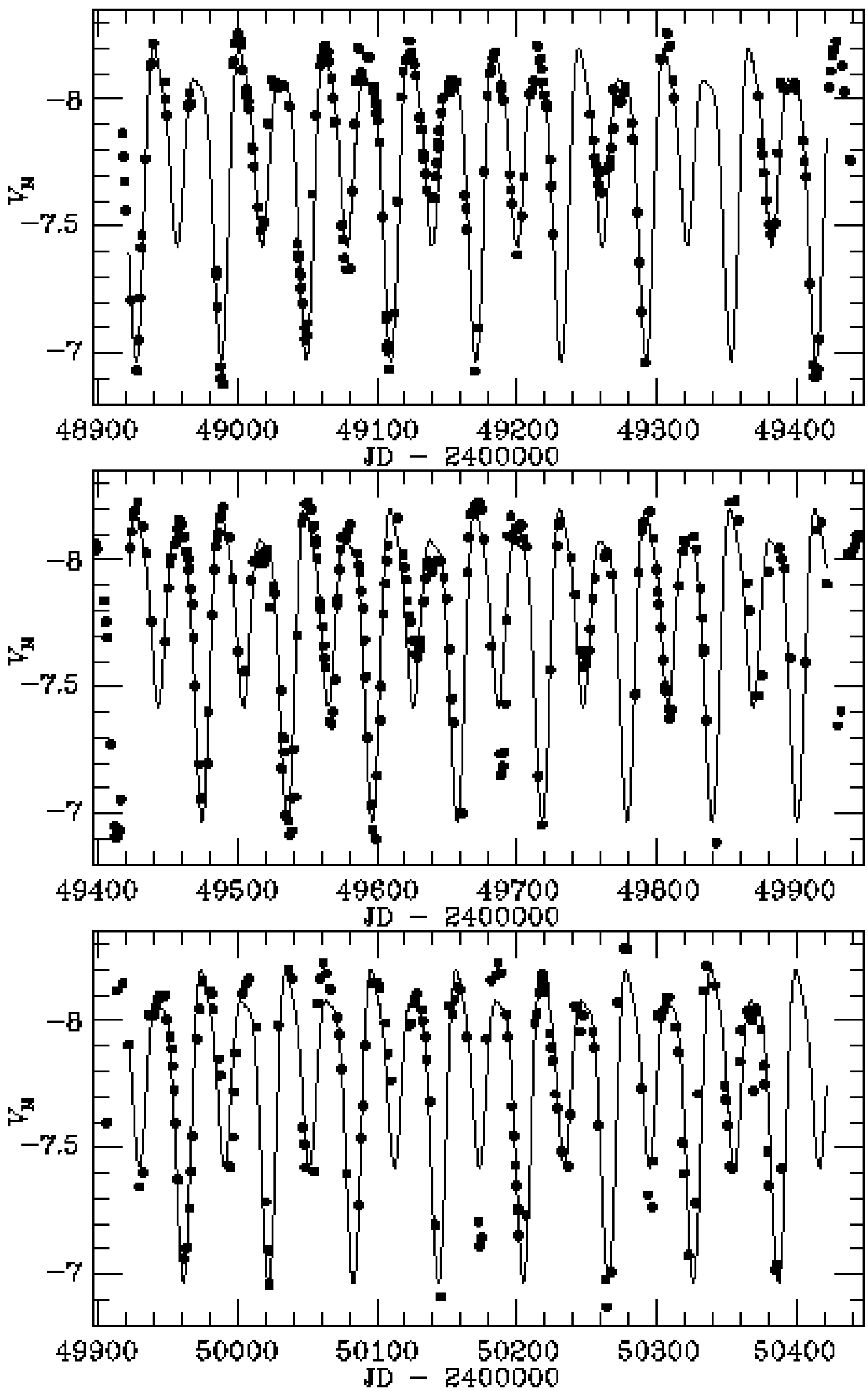
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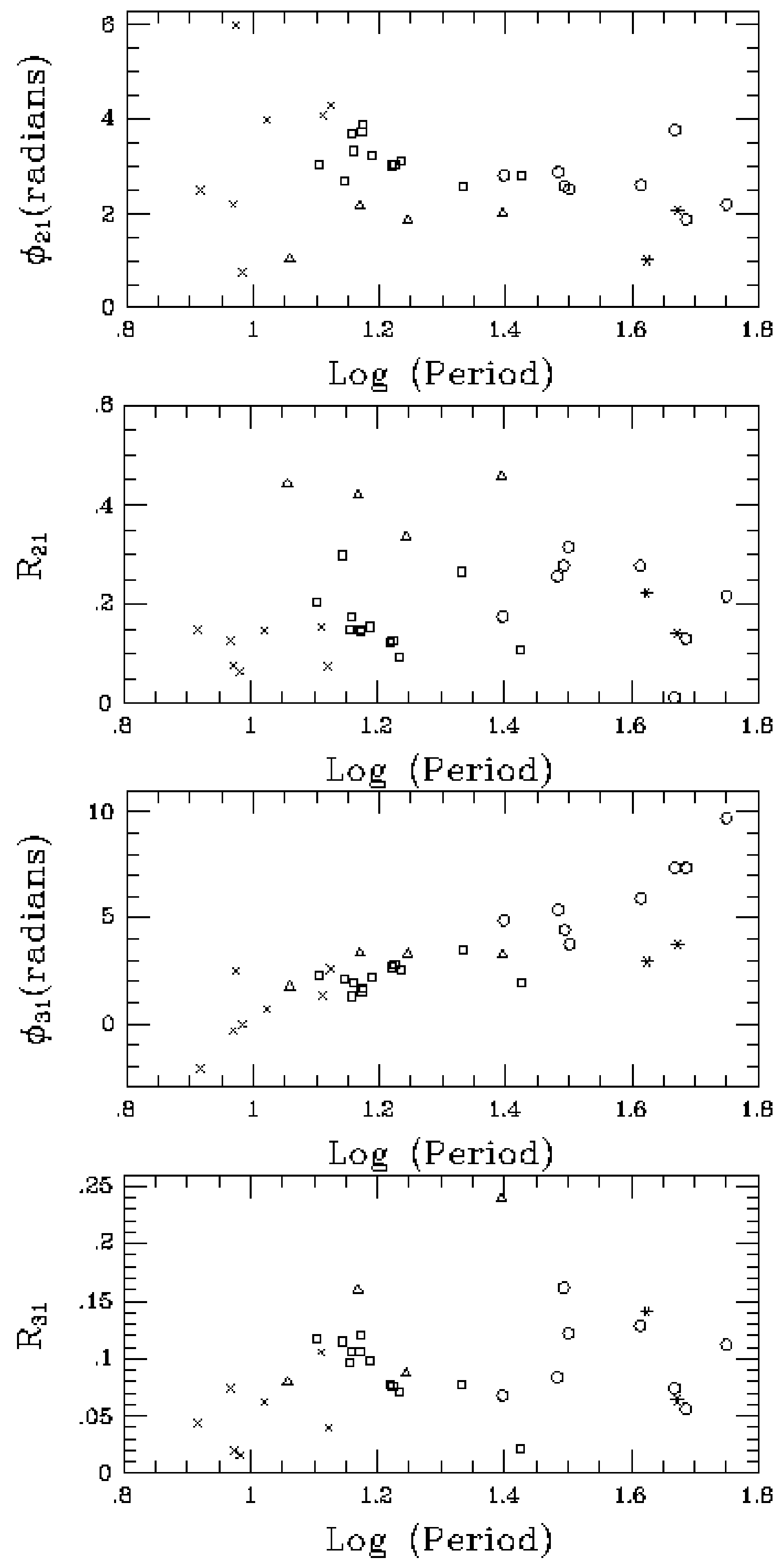
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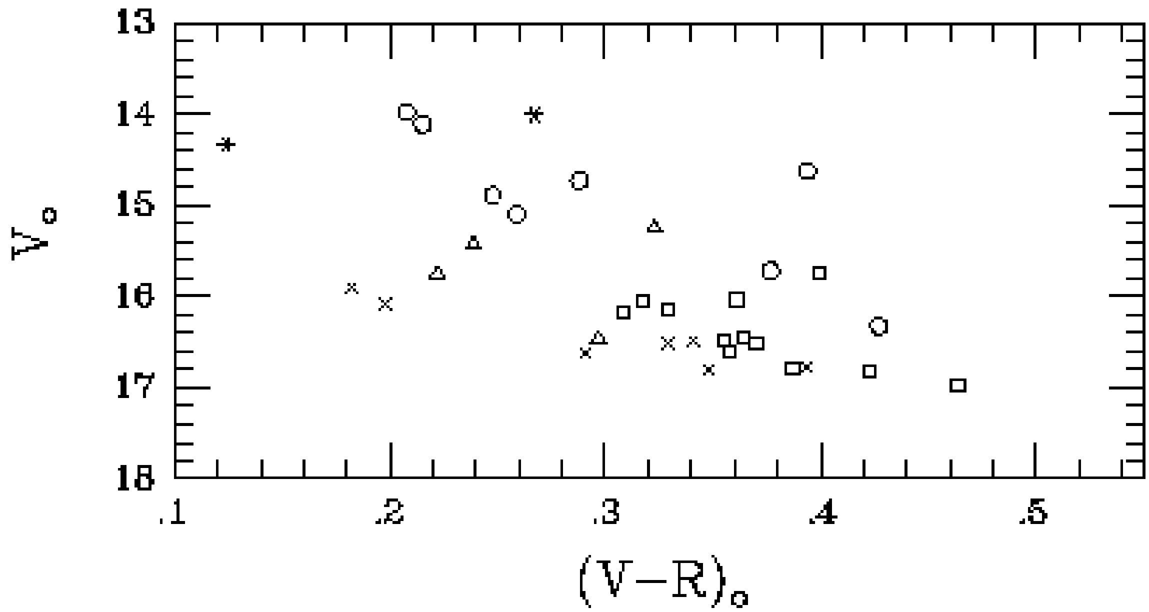
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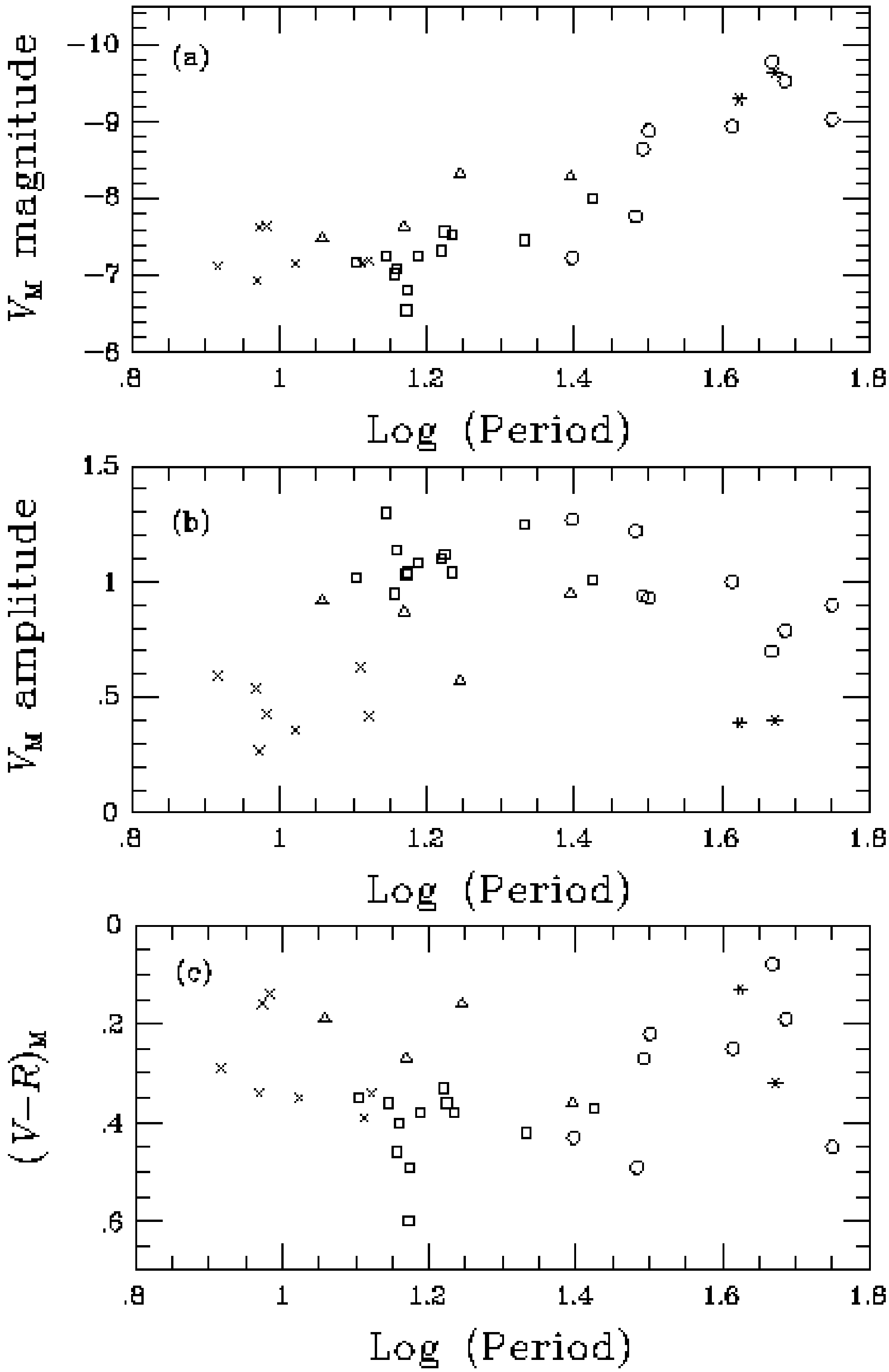
V_o
$(V-R)_o$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Log (Period)
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V_M amplitude
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(c)
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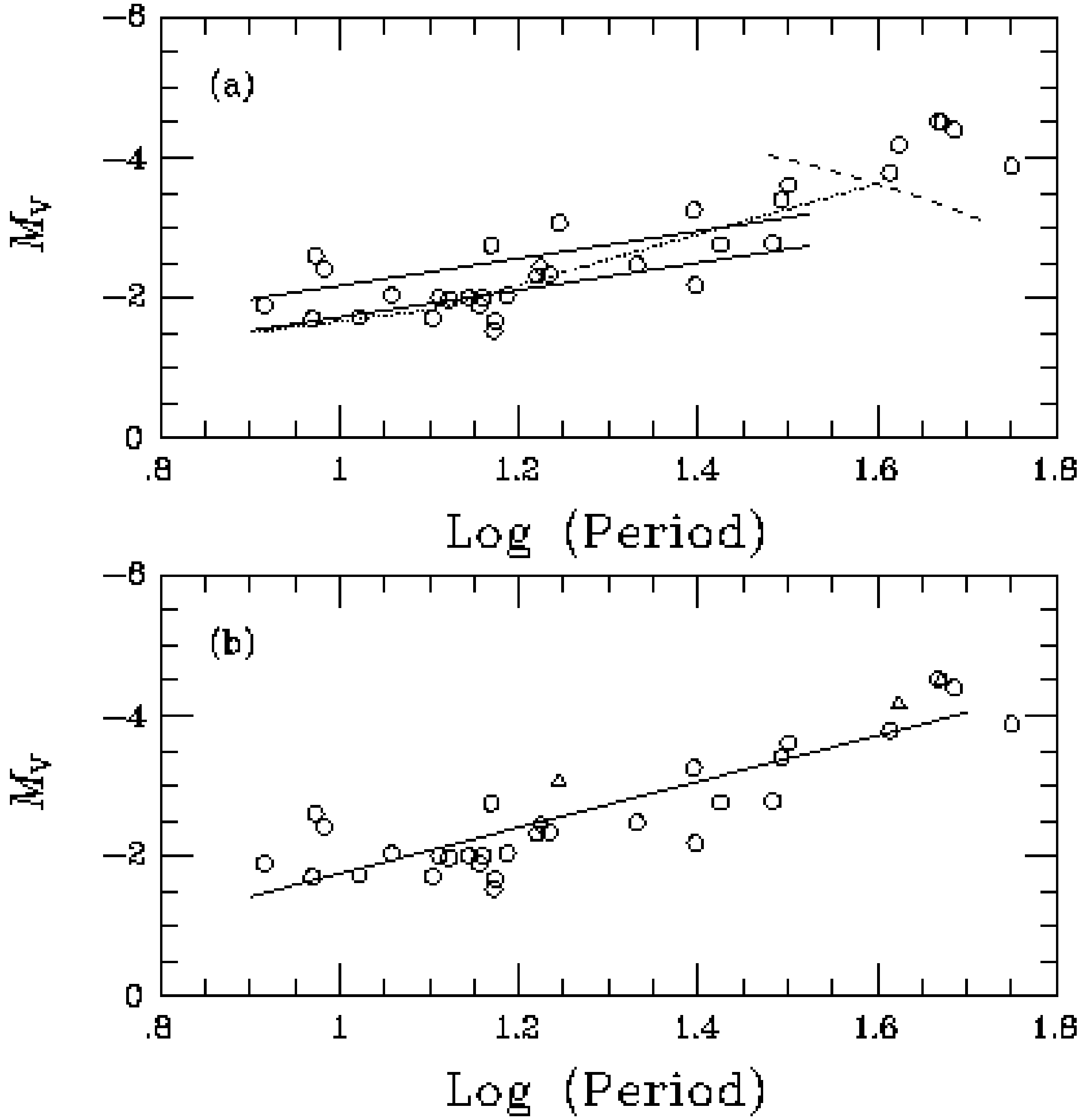
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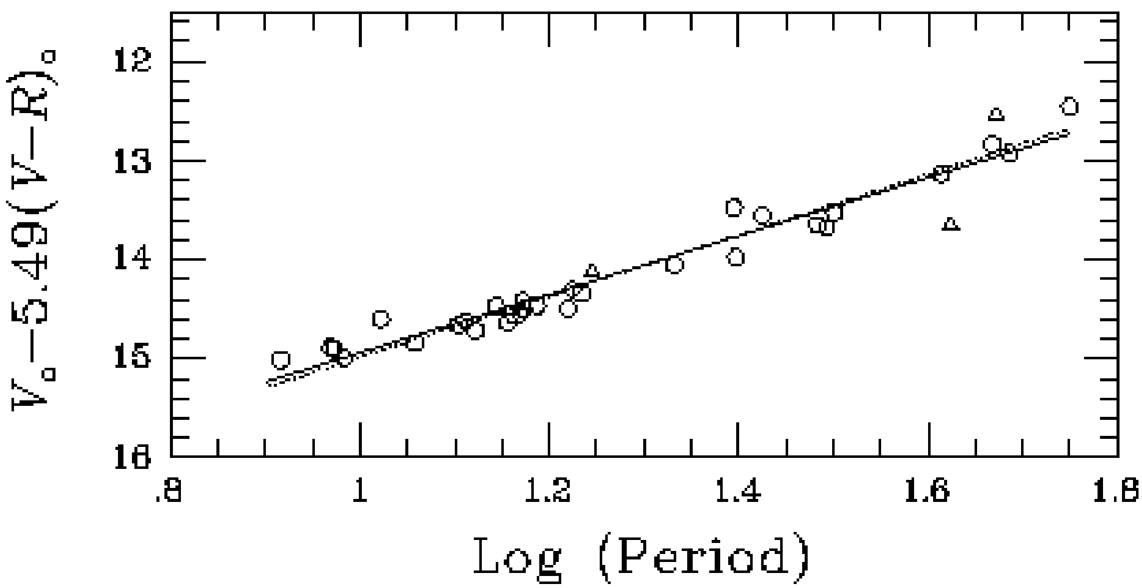
Log (Period)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Log (Period)